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NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20034



NUMERICAL COMPUTATION OF THE SOUND PRESSURE ON A SPHEROIDAL SURFACE
RESULTING FROM A ZONE VIBRATING NEAR A CRITICAL FREQUENCY

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Francis M. Henderson

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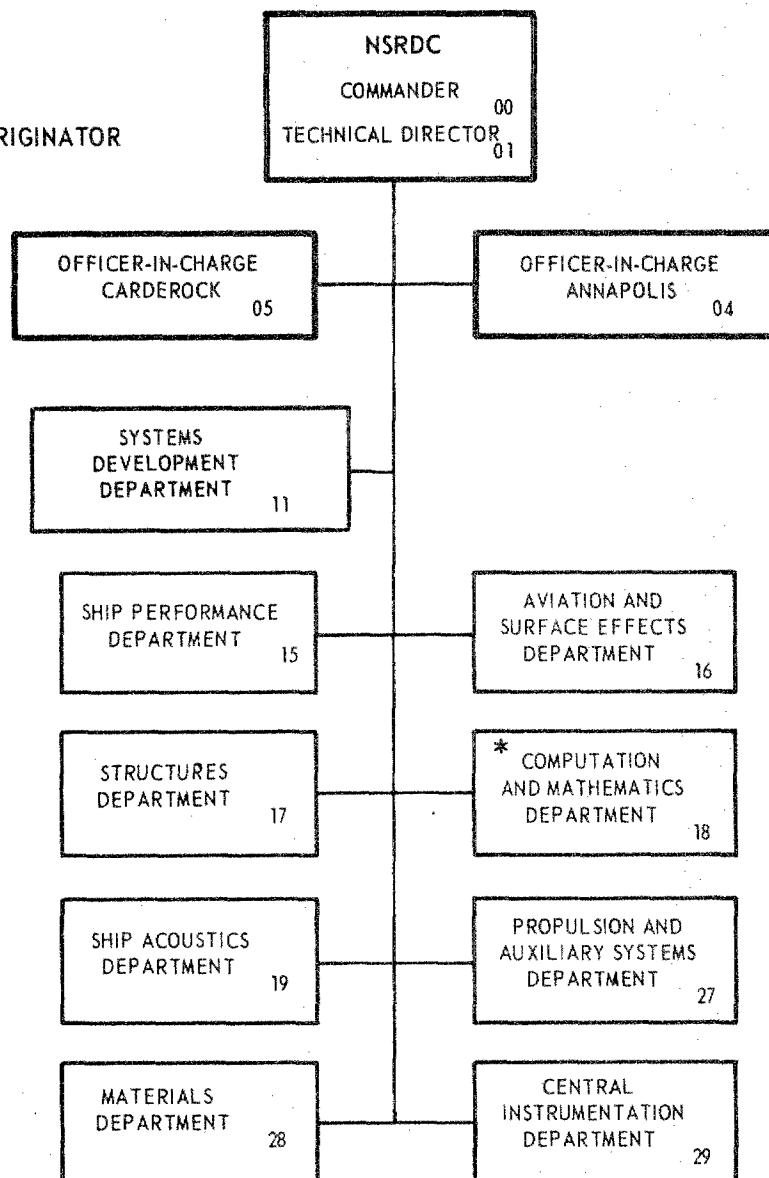
Report 4213

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*REPORT ORIGINATOR



DEPARTMENT OF THE NAVY
NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER
Bethesda, Maryland 20034

NUMERICAL COMPUTATION OF THE SOUND PRESSURE ON A
SPHEROIDAL SURFACE RESULTING FROM A ZONE
VIBRATING NEAR A CRITICAL FREQUENCY

by

Francis M. Henderson



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NOTATION

a, b	Major and minor semiaxes of an ellipse
c	Speed of sound in water
k	Wave number of vibration
p	Sound pressure (complex-valued)
\bar{p}	Normalized sound pressure, $= p/\rho c v_0$
\bar{p}_1, \bar{p}_2	Real and imaginary parts, respectively, of \bar{p}
S	Closed surface of a structure
$v(\underline{y})$	Outward normal velocity S at the point \underline{y} on S
$\bar{v}(\underline{y})$	Normalized velocity, $= v(\underline{y})/v_0$
v_0	An arbitrary velocity
$\underline{y}, \underline{y}'$	Vector points on the structural surface, S
ρ	Mass density of fluid medium
ω	Angular frequency of vibration

ABSTRACT

This report investigates a technique for numerically calculating the sound pressure on a submerged spheroidal baffle that has a narrow ring piston vibrating at a near-critical frequency.

The Helmholtz integral equation relating surface pressure and velocity normal to the structural surface is used to formulate the radiation problem. In the numerical calculation, this equation is represented by approximating matrix equations. These matrix equations correspond to a representation of the shell surface by a finite network of surface elements.

The conditioning of the matrix equation near a critical frequency may make it necessary to use special techniques of solution to obtain the unique surface pressure. One method of dealing with this problem is described here.

Solving the matrix equations by direct methods, we note that the pressure solution near the critical frequency is very sensitive to the way in which acoustic elements are distributed on the surface. Specifically, element distributions biased toward the active zone tend to cause the solution to diverge, primarily in the neighborhood of the zone, whereas distributions favoring the inactive region tend to cause the solution to converge.

These observations provided a basis for the empirical approach to surface model refinement used for this investigation.

Calculated surface pressure curves obtained using the empirical approach show a trend toward agreement with a comparison curve selected from the literature.

ADMINISTRATIVE INFORMATION

The work was conducted in the Mathematical Computation Division, Theory of Structures Branch, under Task Area ZR 014 02 01, Task 13300, Work Units 1-1844-010 and 1-1844-020.

I. INTRODUCTION

The procedure in calculating the steady-state radiated sound pressure on the closed surface of a submerged vibrating structure of arbitrary shape often involves the numerical solution of an integral equation. In such cases, the structural surface is subdivided into a finite number of stations over which the integral equation can be discretely represented by a matrix equation. The solution of the matrix equation (if nonsingular) gives an approximate solution to the integral equation.

If the wave number of vibration is sufficiently different from those wave numbers associated with interior resonant modes of the structural cavity, the matrix equations can be solved by conventional iterative or direct methods to obtain the surface pressure. If, however, the vibration frequency is at or near a critical frequency, the left side of the approximating matrix equations will tend toward singularity, so that special techniques may be required to insure that the correct (unique) solution is obtained. The latter statement implies that the integral equation formulation being used is one for which a pressure solution exists for every frequency. In other words, at a critical frequency, the difficulty encountered will be one of non-uniqueness, rather than nonexistence.

In a survey paper, Chertock¹ discusses a number of special methods for such situations:

- 1) Avoidance of the problem, by, for example,
 - a) Selecting another integral equation formulation that has a different set of critical wave numbers than the one being used,

¹ Chertock, George, "Integral Equation Methods in Sound Radiation and Scattering from Arbitrary Surfaces," Naval Ship Research and Development Center Report 3538 (June 1971).

thereby shifting the vibration wave number out of the neighborhood of the troublesome frequency, or,

b) Using certain high- or low-frequency approximations for the surface pressure, or the results from an incompressible flow ($k \rightarrow 0$), so that no integral equation will have to be solved.

2) Modification of the integral equation to include energy dissipation terms, thereby eliminating the possibility of interior standing waves.

3) Interpolation of the desired solution from results obtained by solving the matrix equations uniquely at two wave numbers, one to the right of and one to the left of the critical wave number.

4) Simultaneous solution of two integral equations.

5) Modifying iterative schemes to expand the range of wave numbers for which convergence can be achieved.

This report will describe still another approach which appears useful for certain types of surface normal velocity distributions, specifically those in which only a relatively small portion of the structural surface is active or vibrating. This approach involves the use of a direct matrix solution algorithm in combination with a judicious distribution of the surface acoustic elements.

II. DESCRIPTION OF THE PHYSICAL PROBLEM

The geometry of the physical problem under consideration here is presented in Figure 1. The narrow zone, indicated by the hatched

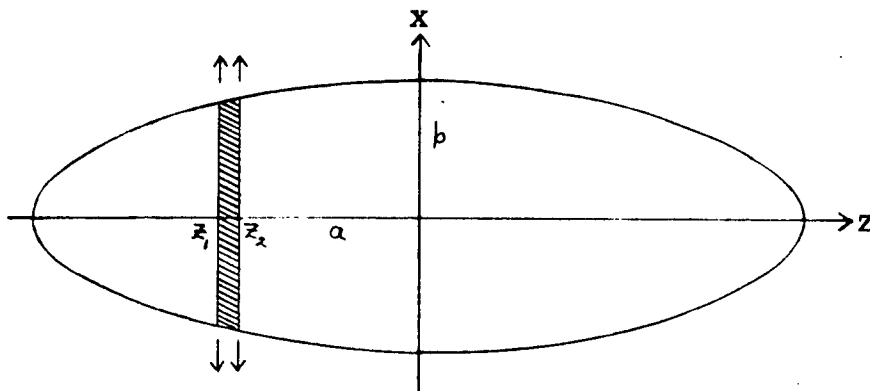


Figure 1 - Vibrating Zone on a Spheroidal Baffle

region, vibrates with rigid body motion in a prolate spheroidal baffle. The structure is submerged in an infinite fluid medium. The prescribed velocity distribution normal to the surface of the zone has unit magnitude, whereas on the baffle it is zero.

The spheroid half-length is $a = 1.00$, the half-width is $b = 0.417$. The width of the vibrating zone, which extends from $z_1 = -0.6198$ to $z_2 = -0.5372$, is 41.3 percent of the total length of the spheroid. The wave number is specified by $ka = 7.26$. An interior resonance mode of the spheroidal cavity² occurs at $ka = 7.19$.

Selection of this particular physical problem provided two advantages for the current investigation: (1) a detailed solution for

² Chertock, G., "Solutions for Sound-Radiation Problems by Integral Equations at Critical Wave Numbers," Journ. of the Acoustical Soc. of Am., Vol. 47, No. 1 (Part 2) (1970).

the surface pressure by another special method was already available for comparison; and (2) only a relatively small part of the total surface area in motion, a property that proved essential for the method of this report.

III. INTEGRAL EQUATION FORMULATION AND SURFACE MODELING

Although the physical problem just described is amenable to solution by analytic methods (since the scalar wave equation is separable in the prolate spheroidal coordinate system), the approach used in this investigation involves the numerical solution of an integral equation formulation. The particular formulation used is the Helmholtz equation for sound pressure on the structural surface

$$\begin{aligned} \frac{\bar{p}(\underline{y}')}{2} - \iint_S \bar{p}(\underline{y}) \frac{\partial}{\partial n} \left[\frac{e^{ik|\underline{y}' - \underline{y}|}}{4\pi |\underline{y}' - \underline{y}|} \right] dS \\ = ik \iint_S \bar{v}(\underline{y}) \frac{e^{ik|\underline{y}' - \underline{y}|}}{4\pi |\underline{y}' - \underline{y}|} dS \end{aligned} \quad (1)$$

where

$\bar{p} = p/\rho c v_0$	is the nondimensional sound pressure
\underline{y}' and \underline{y}	are vector points on the structural surface S
$i = \sqrt{-1}$	
$k = \omega/c$	is the wave number of vibration
$\bar{v}(\underline{y}) = \frac{v(\underline{y})}{v_0}$	is the nondimensional velocity

The computer program, **XWAVE**,^{*} was used to calculate the coefficients of a matrix equation

$$M\bar{p} = B\bar{v} \quad (2)$$

which is taken to approximate Equation (1). Equation (2) is based upon a subdivision of the structural surface into a finite number of areas.

The acoustic modeling of the spheroidal surface is facilitated through the automatic data generation module of the **XWAVE** program, as detailed by Henderson.³ It is sufficient for the present discussion to examine the following figure reproduced from his report. As

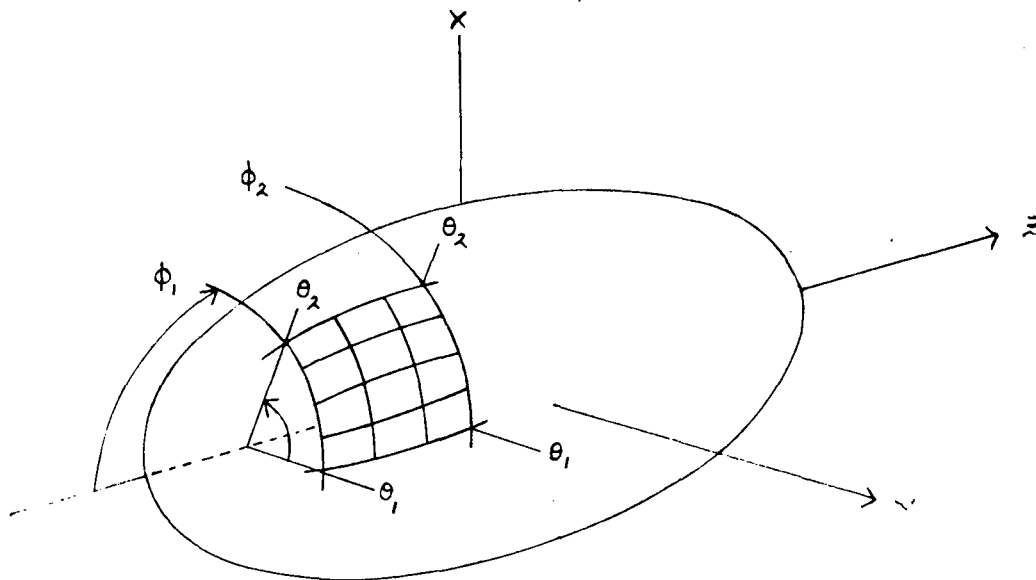


Figure 2 - Acoustic Modeling of Spheroidal Surface

* Informally documented in Technical Note CMD-24-71, "Computation of the Sound Pressure Field About Submerged Vibrating Structures by a Method of G. Chertock," by F. Henderson (August 1971).

³ Henderson, F. M., "Radiation Impedance Calculations With the XWAVE Computer Program," Naval Ship Research and Development Center Report 4033 (Mar 1973).

shown, a typical surface "region" is defined by its extent in latitude and longitude. The region is subdivided according to two specified integers, n and m , into n bands of latitude with $(\phi_2 - \phi_1)/n$ degrees, each having n acoustic surface elements per band, with $(\theta_2 - \theta_1)/m$ degrees.

Figure 1 indicates that the surface geometry and normal velocity boundary conditions for the problem under consideration are rotationally symmetric. The resulting surface pressure will also have this property. Since the XWAVE program at present recognizes only coordinate axis symmetry planes, the nonredundant part of the surface geometry which must be supplied is one quarter of the whole, as is shown in Figure 3.

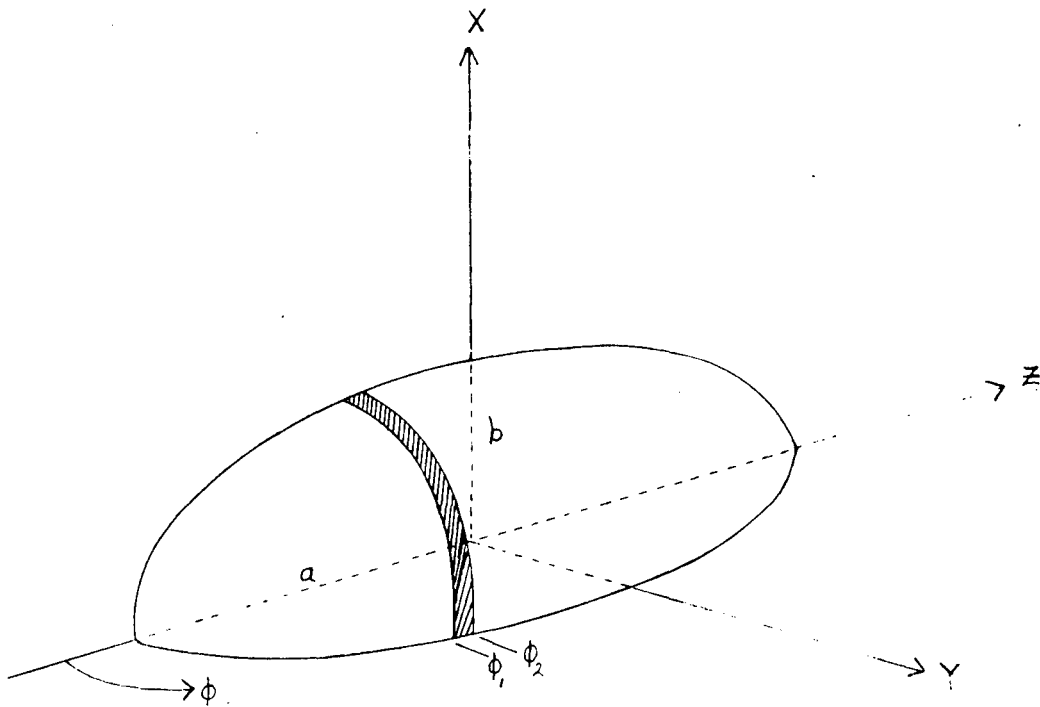


Figure 3 - Geometry of Spheroidal Surface Input to XWAVE

Rotational symmetries are used at matrix generation time when the induced effect of all acoustic surface elements within a quarter band of elements is concentrated at the first acoustic element on the positive side of the meridian $\theta = 0$. The order of Equation (2) is therefore reduced to the total number of such surface elements along that meridian.

The region of the vibrating zone is denoted in Figure 3 by hatched lines. Using the equation for an ellipse in the x-z plane and noting the extent of the zone along the z-axis (pg. 5), the region is found to be bounded by $\phi_1 = 27.833^\circ$ and $\phi_2 = 33.214^\circ$.

IV. A MATRIX ALGORITHM FOR SINGULAR VALUE DECOMPOSITION

Before the approach used for the critical frequency calculation is discussed, a subroutine (CSVD) which entered into the preliminary investigation (elaborated in the next section) should be briefly considered.

The algorithm is described by Businger and Golub.⁴ The particular feature of this subroutine which is useful for this investigation is its capability to compute unitary matrices U and V which will diagonalize a matrix, A, with complex-valued elements as follows

$$U^*AV = \Sigma \quad (3)$$

⁴ Businger, P. A. and G. H. Golub, "Singular Value Decomposition of a Complex Matrix," Algorithm 358, Communications of the ACM, Vol. 12, No. 10 (Oct 1969).

The asterisk (*) indicates Hermitian transpose and Σ is a diagonal matrix for which the non-zero elements are the singular values, σ_i , of A. The matrices U and V are such that $\|A - U\Sigma V^*\|$ relative to $\|A\|$ is negligible.⁴

The particular version of CSVD used was obtained from the program listing provided in reference 4. To insure that the program deck contained no errors due to transcribing from the listing, various tests were run with it using both real and complex matrices. In particular, the relationship given in Equation (3) was verified for various complex matrices and then used in solving systems $M\bar{p} = f$ (Equation (2) with $f = B\bar{v}$) similar to those associated with the problem under consideration. The solutions were obtained by calculating

$$\bar{p} = V\Sigma^{-1}U^*f \quad (4)$$

in which diagonal elements of Σ^{-1} are inverses of the singular values of M.

The solutions found for \bar{p} using CSVD were further checked by submitting these same matrix systems to a different subroutine, CGLESM, obtained from the CDC Math Science Library. In all cases, the solutions obtained using this alternate algorithm, agreed with those obtained using CSVD.

For this investigation, the subroutine CSVD was not incorporated directly into the XWAVE program. For a particular modeling of the spheroidal surface, XWAVE was run solely to establish values for the elements of the matrix M and the vector f. These values were then supplied as input to a second computer run in which the CSVD subroutine calculated the surface pressure solution, \bar{p} .

The CSVD version used here will handle matrices (full, complex) of orders up to 100x100. The largest order solved during this investigation was 69x69.

V. APPROACH

As the wave number of vibration moves closer to a critical wave number of the spheroidal cavity, the matrix M in Equation (2) tends toward singularity and the solution for \bar{p} tends toward non-uniqueness. The iterative method of solution (Gauss-Seidel) presently incorporated in the XWAVE program produces divergent results in these circumstances.

A possible way of resolving nonuniqueness was suggested to the author by Dr. Robert N. Buchal of the Naval Research Laboratory. Using his approach, Equation (2) would be transformed, using unitary matrices, to the form

$$\Sigma q = U*f \quad (5)$$

where $\Sigma = U*MV$ is a diagonal matrix for which the diagonal elements are the singular values of M , and the value of q is $V*\bar{p}$. This approach anticipates the case in which Σ allows a partitioning based upon the relative sizes of its diagonal elements (these are real numbers) which occur in descending order of magnitude. For purposes of partitioning, it must be possible to group these elements by size as either large or ignorable (having small and zero values). If the vector $U*f$ admits a similar and compatible partitioning, a solution can be obtained for q from the partitions of Equation (5)

containing only elements of significant magnitude. The neglect of the partitions with small- or zero-valued elements is therefore a means for discriminating against those components of the solution, q , which would tend toward indeterminacy.

In order to test the applicability of this approach to the case $ka = 7.26$, the spheroidal surface was first modeled (Model A) as indicated in Table 1 (p. 16). This surface model, and the value for ka formed the input to XWAVE which generated the corresponding coefficient matrix, M , and vector f . These then became data input to CSVD which calculated the diagonal elements of Σ .

As indicated by the range of singular values computed for M (Table 2), no zeros (to machine precision) were obtained, nor was there any readily discernible boundary between relatively large and ignorably small values, since the smallest value computed was still 7.894 percent of the largest value. These effects were partially due to the ka not being sufficiently close to the critical frequency and the matrix M being of a reduced order (p. 9).

Since there appeared to be no obvious separation of the diagonal elements of Σ into categories of large and ignorably small, or at best this was a borderline case, it seemed appropriate to look at a solution as obtained from Equation (4). The result of this computation is shown in Appendix A (Model A).

Since the solution-points computed generally reflect the shape of the comparison curve, it was of interest to observe their behavior further through several refinements of the surface model. The refinements represent successive increases in the density of acoustic elements primarily on the active zone. The results from each refinement are given for the models B, C, E, F, G, H, L, and M (Table 1). For convenience, these models are grouped according to number of

bands (n) on the active zone; the first group having 2 bands (Models A, B, C), the second having 3 bands (Models E, F, G, H), and the third having 4 bands (Models L and M).

The results of the surface pressure computations using these models reveal that the solution remains relatively stable except for those points lying close to the active zone where the divergence is noticeable. The latter effect is most evident in the imaginary part (\bar{p}_2) of the solution. The ranges of singular values for these models show relatively little deviation from those obtained for the original model, A.

At this stage of the investigation, the process of successively increasing the density of elements primarily on the active zone rather than on the baffle surface was reversed to determine the effect on the solution. Two models, D and I, were established for this test. As indicated in Table 1, these models represent refinements of Models B and F, respectively, which, increased both the number of bands and the number of elements per band covering the baffle. Comparing the corresponding pressure solutions (Appendix A), we note that this refinement of Model B results in a reduction of the maximum value of \bar{p}_2 from 0.455 to 0.440 and of Model F in a reduction from 0.476 to 0.458.

In view of the results just described, and assuming the reduction of maximum values is convergent with additional refinement, the following test steps evolved as an alternative approach to obtaining improved solutions via modeling.

Step 1 Begin with an initial acoustic modeling of the surface and compute the singular values of the matrix $[M]$.

Step 2 If, as in the present case, the magnitudes of the singular values are not widely separated, and no essentially small or zero values occur, calculate the pressure solution for the initial surface model and for a series of refinements of the model, using the convention of placing a higher density of surface elements on the vibrating zone. One should make certain that the refinements of the initial model do not lead to singular values that are widely separated, small, or zero-valued.

Step 3 If the pressure solution for the series of surface models tends to diverge, select one of the models and try to improve the solution by making successive refinements to the model which vary the number of acoustic elements on the inactive part of the surface only. The economics of the computational process suggest that the model selected should be one of those that exhibits lower maximum values in the pressure solution. More particularly, it should be the one giving the least maximum value with yet a sufficient number of points to delineate the pressure curve in areas where peaks may occur.

The last step of the proposed modified method was tested for the present application by continuing the refinement of the surface model D. This model has three bands on the vibrating zone -- about the minimal number -- with one solution point (complex) per band, suitable for use, considering the rather steep peak indicated in the \bar{p}_2 curve. The number of circumferential elements in each of these bands is 16, corresponding with the least maximum value of \bar{p}_2 obtained among the original series of 3-band models (E, F, G, H). (See Appendix A.)

From the successive refinements of surface model D, results were also obtained for two of the intermediate models, I and J, and

for the final model considered, K. (See Appendix A.) As indicated in Table 1, these models reflect an increase in both the number of bands and the number of elements per band over the baffle surface. The maximum value of \bar{p}_2 is further reduced in each case, and, since the increment of reduction is less with each refinement, the reduction process appears to be converging. This trend is not evident in comparing the results for Models J and K, since the results for several intermediate models were omitted for brevity. Although the rate of reduction appears extremely slow, the test confirms that use of the modeling procedures described can provide improvement in the pressure solution at points where maximum divergence from the comparison curve occurs.

In the process of successively refining Model D, it was noted that although an increase in the number of surface elements on the baffle has the effect of decreasing the maximum \bar{p}_2 value obtained, it may not in itself assure the best solution in general. For example, although the J Model gives a higher maximum value of \bar{p}_2 than the K Model, it still produces a generally closer fit to the comparison curve for \bar{p}_2 . This result suggests that the acoustic elements could have been more effectively distributed on the baffle of the latter model.

**TABLE 1 - XWAVE SURFACE MODELS OF SPHEROIDAL
SURFACE USED FOR COMPUTATIONS**

Model	Region	ϕ_1^0	ϕ_2^0	n	m	Effective Elements*
A	1	0	1	1	1	868
	2	1	27.83	5	8	
	3	27.833	33.214	2	8	
	4	33.214	179	20	8	
	5	179	180	1	1	
B	(Same	as for	A)	1	1	930
				5	8	
				2	16	
				20	8	
				1	1	
C	(Same	as for	A)	1	1	1058
				5	8	
				2	32	
				20	8	
				1	1	
D	(Same	as for	A)	1	1	2754
				6	16	
				2	16	
				35	16	
				1	1	
E	(Same	as for	A)	1	1	866
				4	8	
				3	8	
				20	8	
				1	1	
F	(Same	as for	A)	1	1	962
				4	8	
				3	16	
				20	8	
				1	1	

* The number of effective elements is calculated by taking the sum of the products $n \times m$ for regions except the first and last, multiplying this sum by 4 (corresponding to principal axis symmetry planes, Figure 3) and adding the two single elements (spheroidal caps) for the first and last regions.

**TABLE 1 - XWAVE SURFACE MODELS OF SPHEROIDAL
SURFACE USED FOR COMPUTATIONS - Continued**

Model	Region	ϕ_1^0	ϕ_2^0	n	m	Effective Elements*
G	(Same	as for	A)	1	1	1154
				4	8	
				3	32	
				20	8	
				1	1	
H	(Same	as for	A)	1	1	1346
				4	8	
				3	48	
				20	8	
				1	1	
I	(Same	as for	A)	1	1	2752
				6	16	
				3	16	
				34	16	
				1	1	
J	(Same	as for	A)	1	1	3714
				9	16	
				3	16	
				46	16	
				1	1	
L	(Same	as for	A)	1	1	1250
				4	8	
				4	32	
				19	8	
				1	1	
M	(Same	as for	A)	1	1	1506
				4	8	
				4	48	
				19	8	
				1	1	
K	1	0	1	1	1	13,338
	2	1	10	3	16	
	3	10	27.84	8	55	
	4	27.84	33.214	3	16	
	5	33.214	169	50	55	
	6	169	179	3	16	
	7	179	180	1	1	

TABLE 2 - RANGES OF COMPUTED SINGULAR VALUES
CORRESPONDING TO SURFACE MODELS

Model	Singular Values	
	Maximum	Minimum
A	1.1652	0.091981
B	1.1654	0.091841
C	1.1655	0.091709
D	1.1545	0.090437
E	1.1672	0.088481
F	1.1675	0.088430
G	1.1676	0.088387
H	1.1677	0.088362
I	1.1571	0.089297
J	1.1342	0.090907
K	1.1419	0.08953
L	1.1770	0.085348
M	1.1771	0.085349

ACKNOWLEDGMENT

The author is indebted to Dr. Robert N. Buchal of the Acoustic Environmental Support Detachment of the Office of Naval Research for his basic ideas leading to this investigation, his helpful discussions during the course of the work, and his reference to the subroutine CSVD.

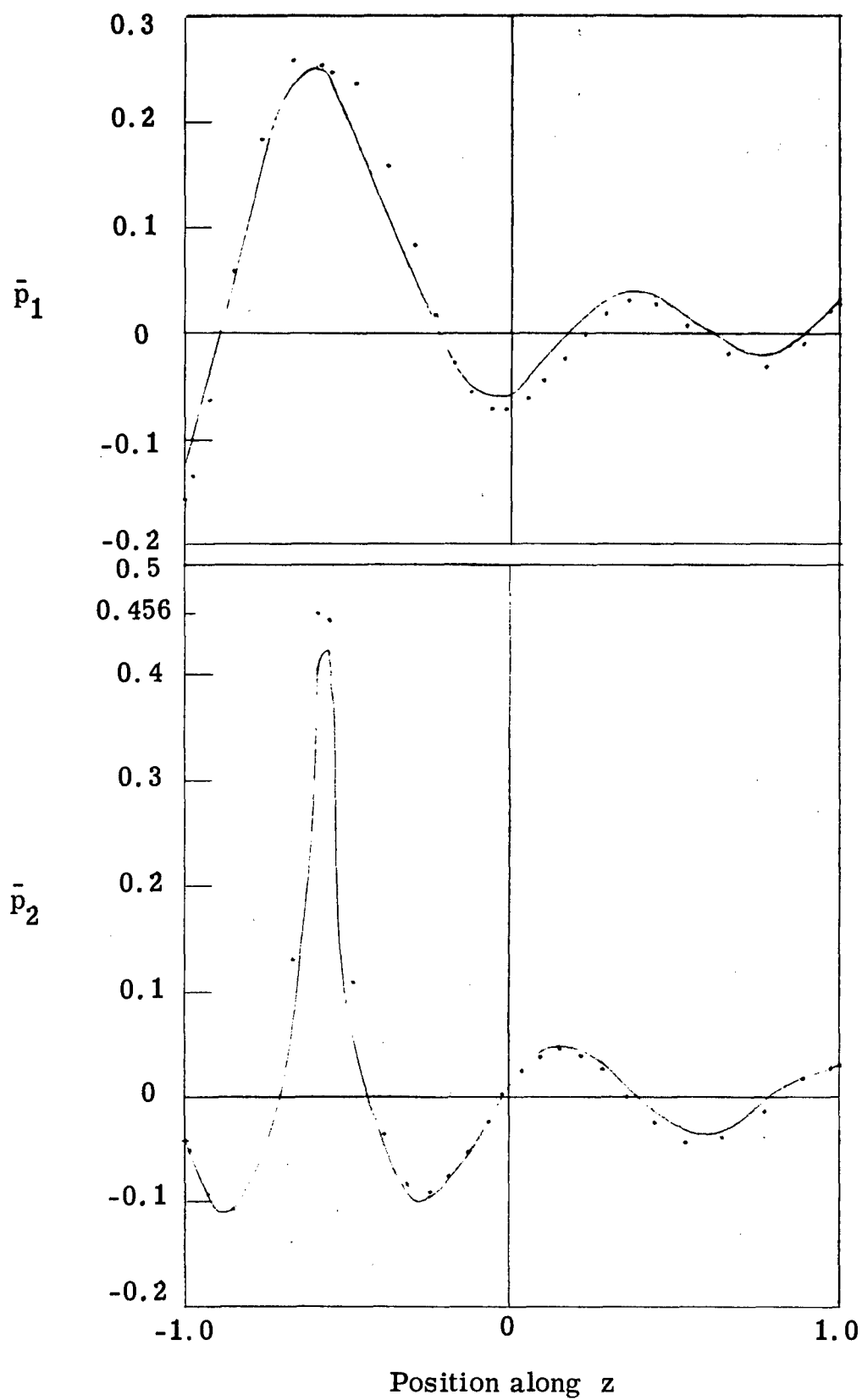
APPENDIX A

COMPUTED RESULTS

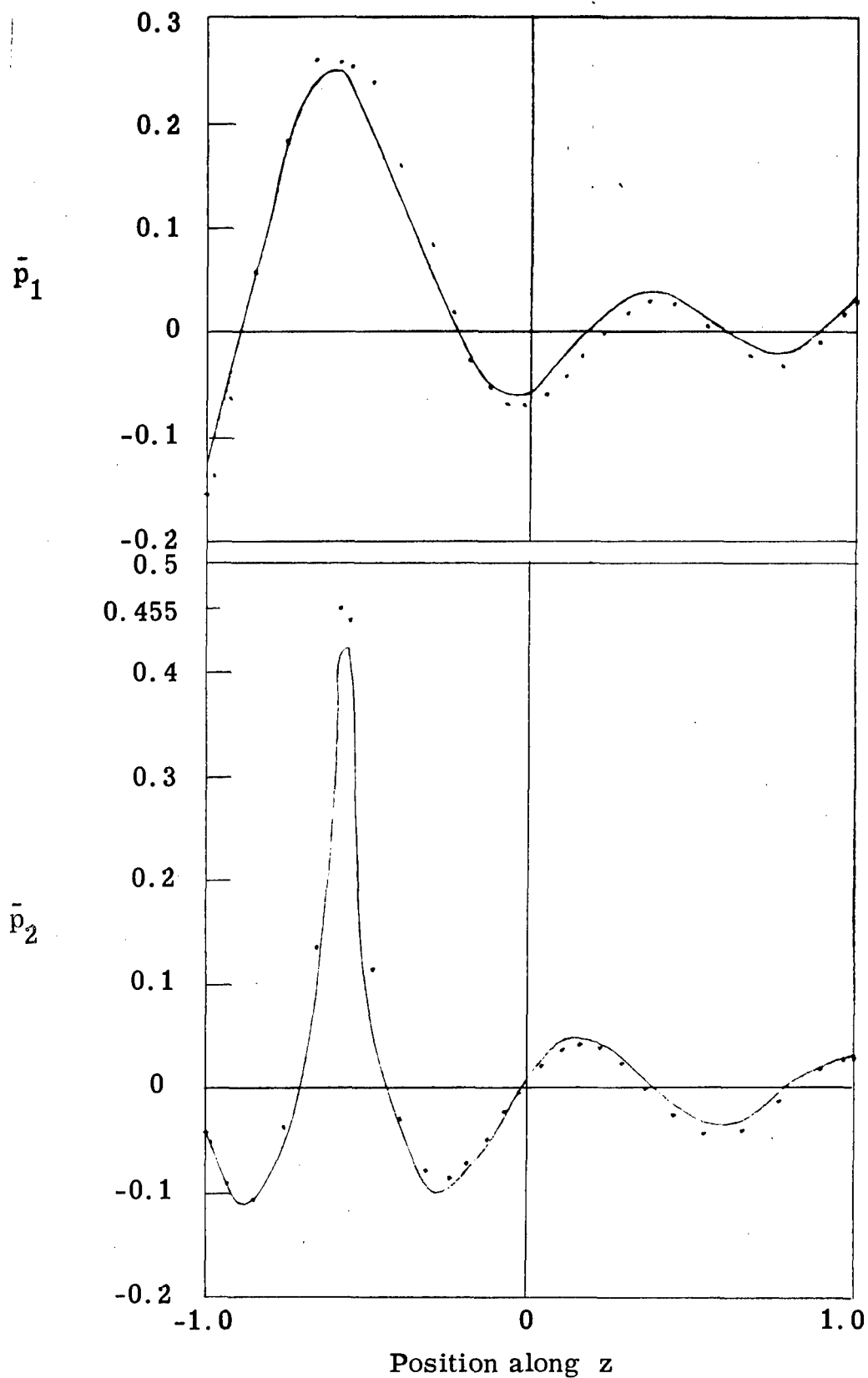
This section presents the results for surface pressure computed using surface models A through M. In each case, the dotted lines represent the solutions calculated using the programs **XWAVE** and **CSVD**, whereas the solid line is the comparison curve.⁵ The ordinate of the maximum value of \bar{p}_2 is labeled in each plate.

The plates are arranged in the order in which they are discussed in the text.

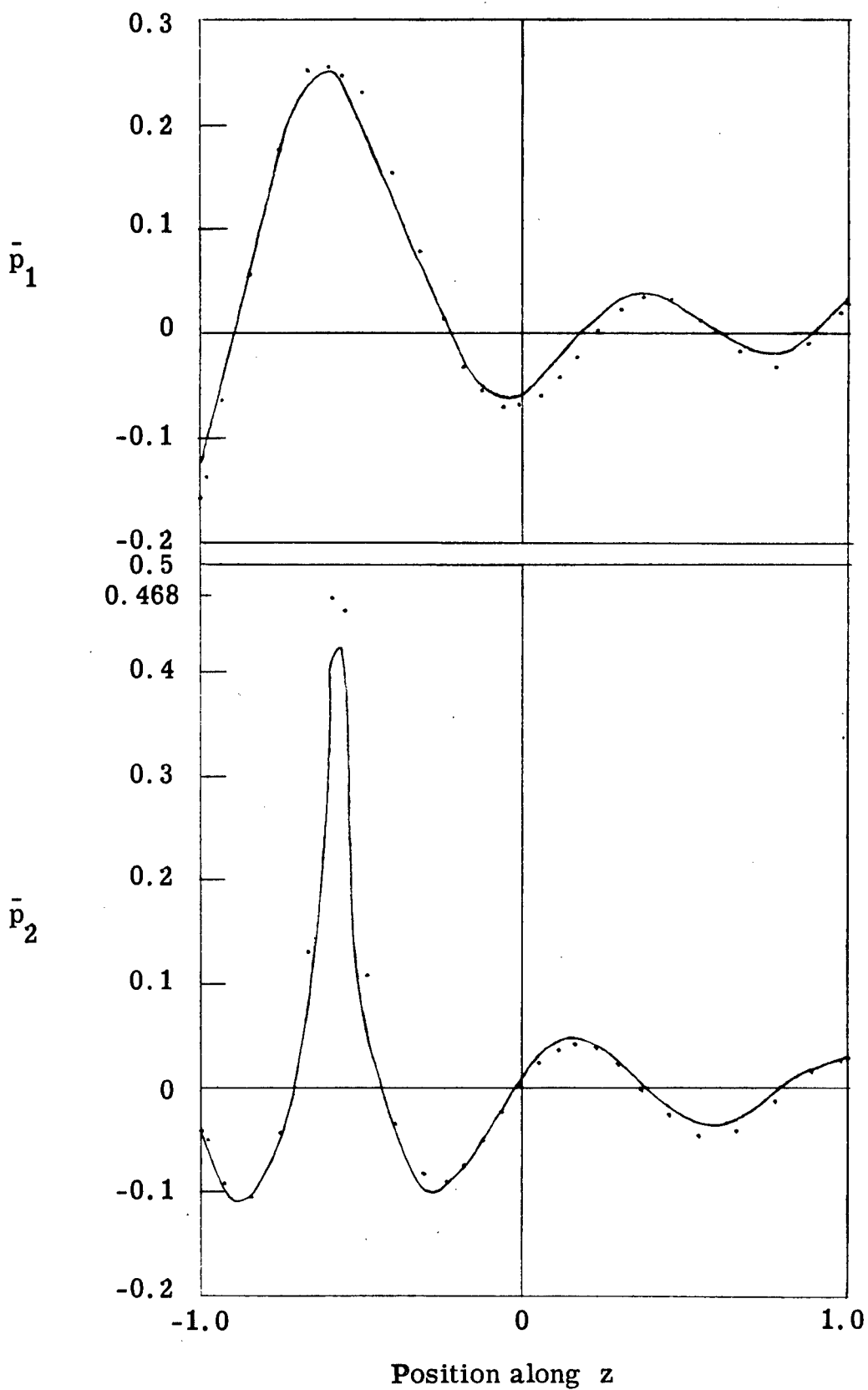
⁵ Chertock, G. and M.A. Grosso, "Some Numerical Calculations of Sound Radiation from Vibrating Surfaces," Naval Ship Research and Development Center Report 2109 (Mar 1966).



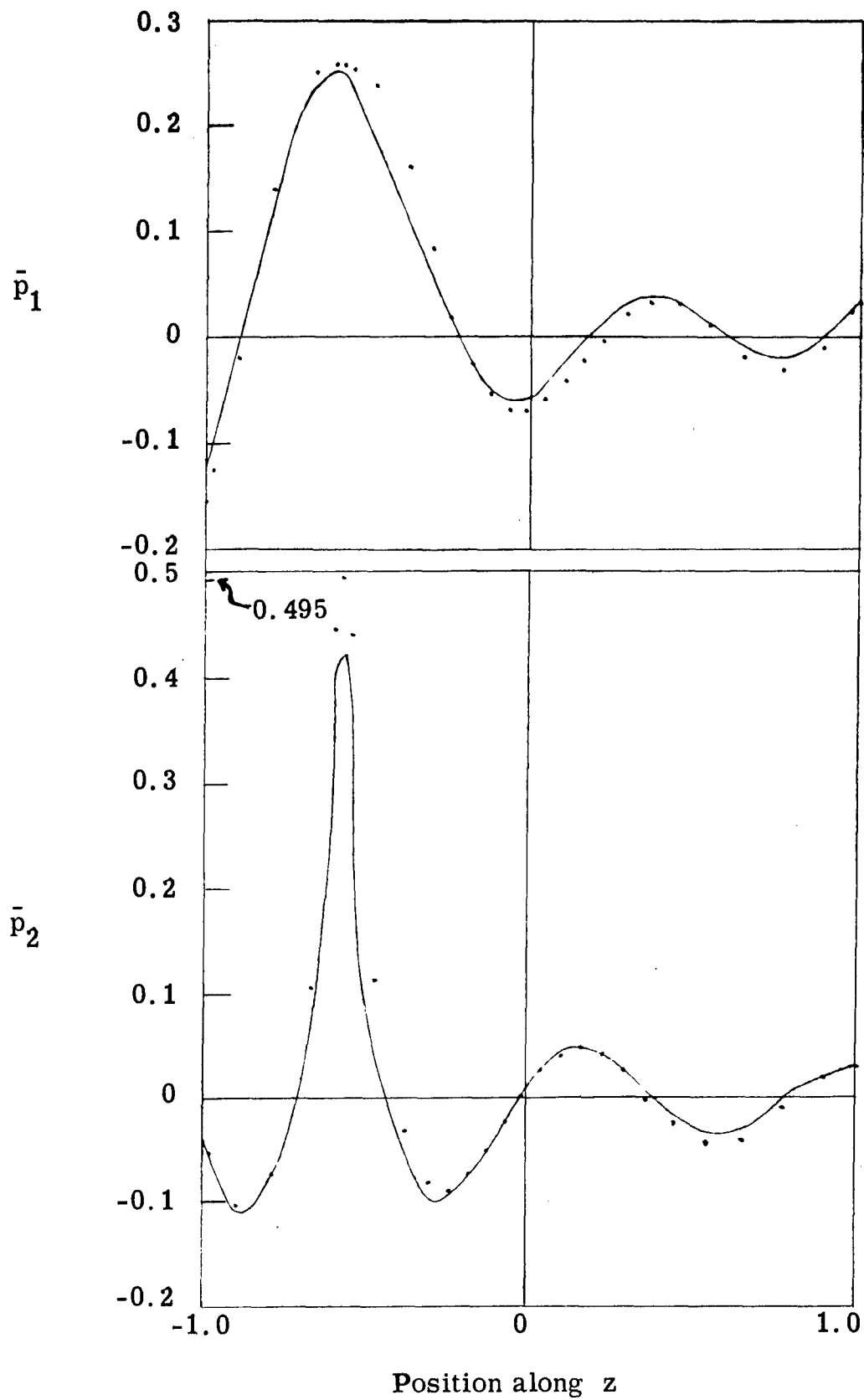
Model A, $ka = 7.26$



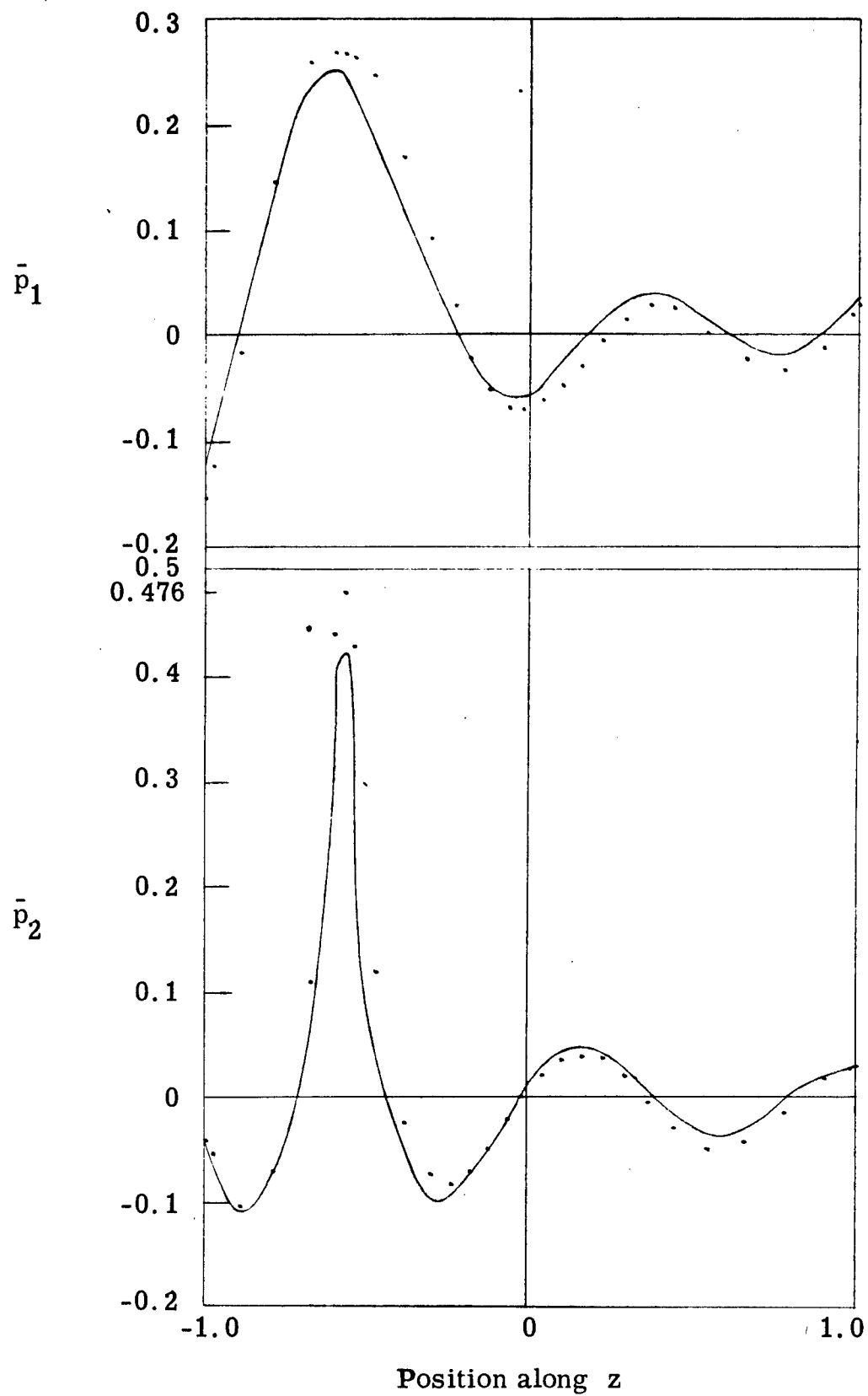
Model B, $ka = 7.26$



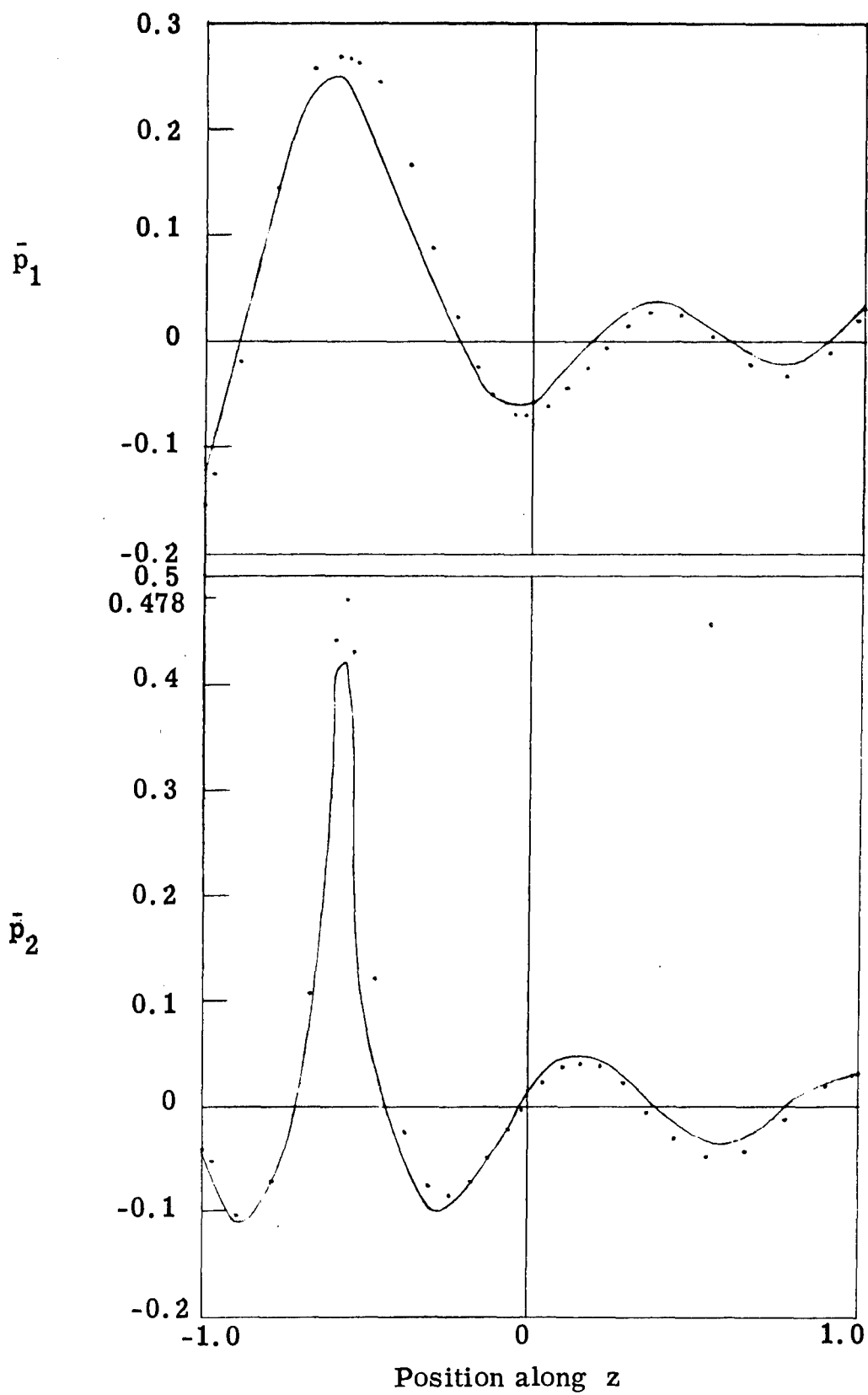
Model C, $ka = 7.26$



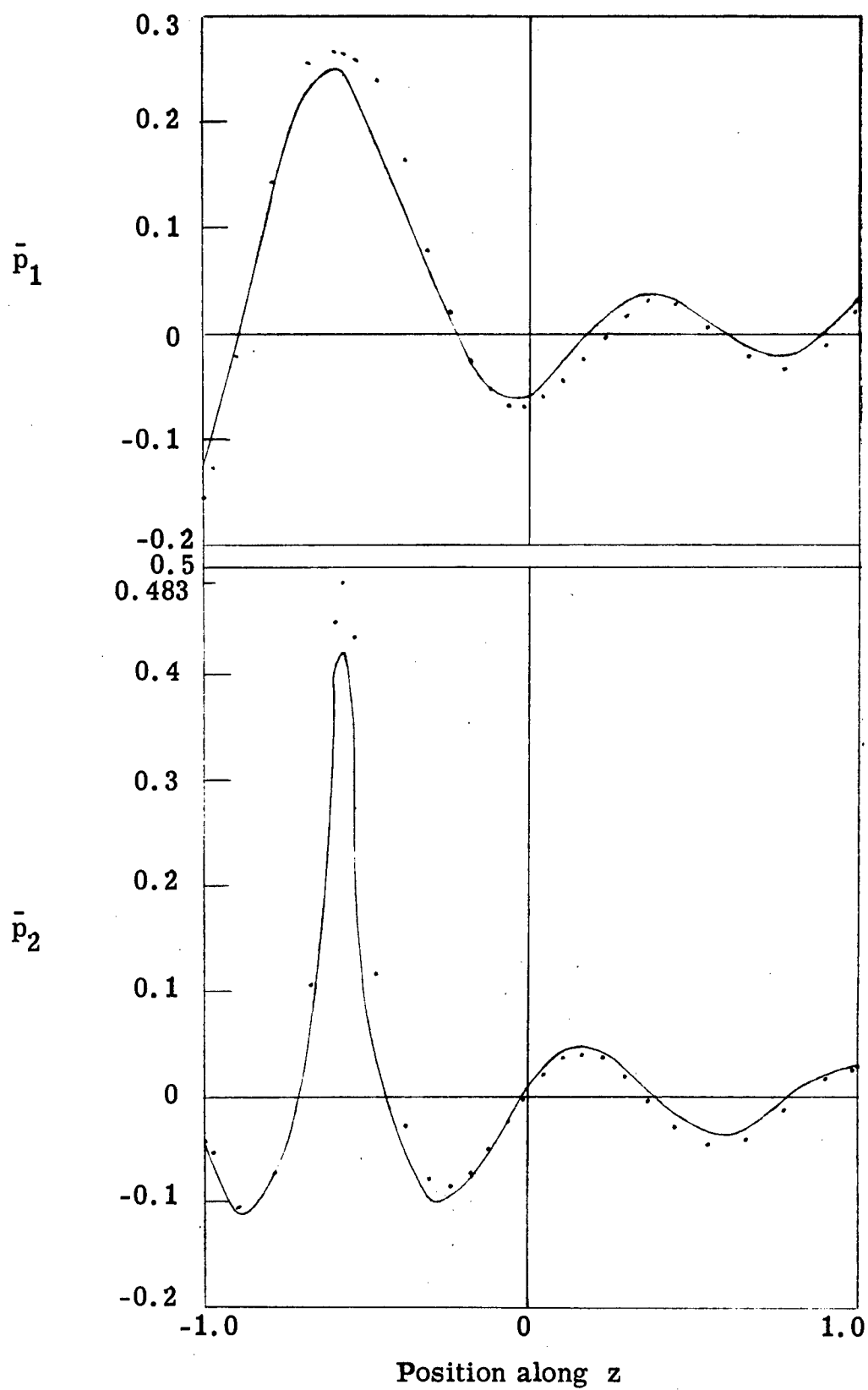
Model E, $ka = 7.26$



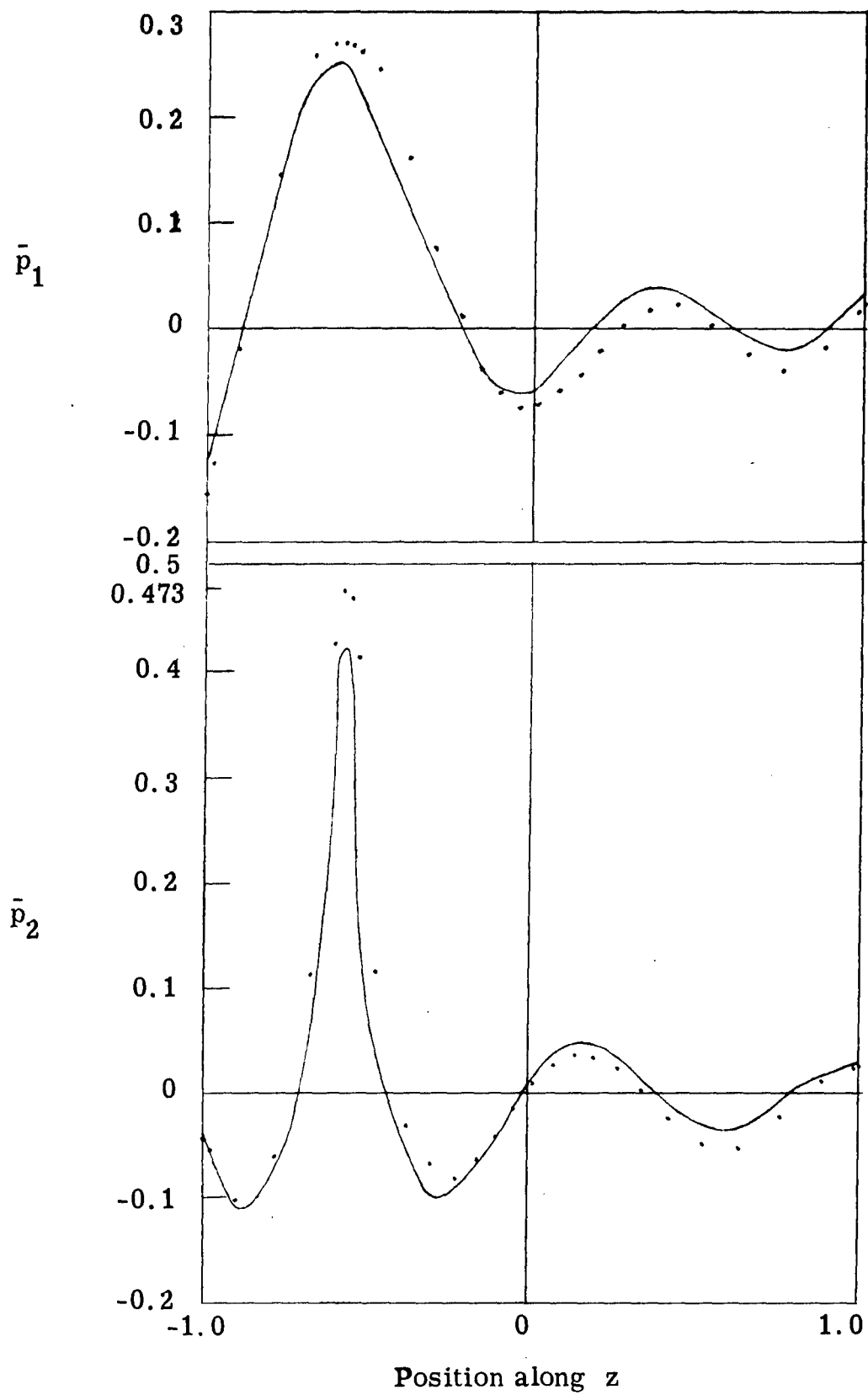
Model F, $ka = 7.26$



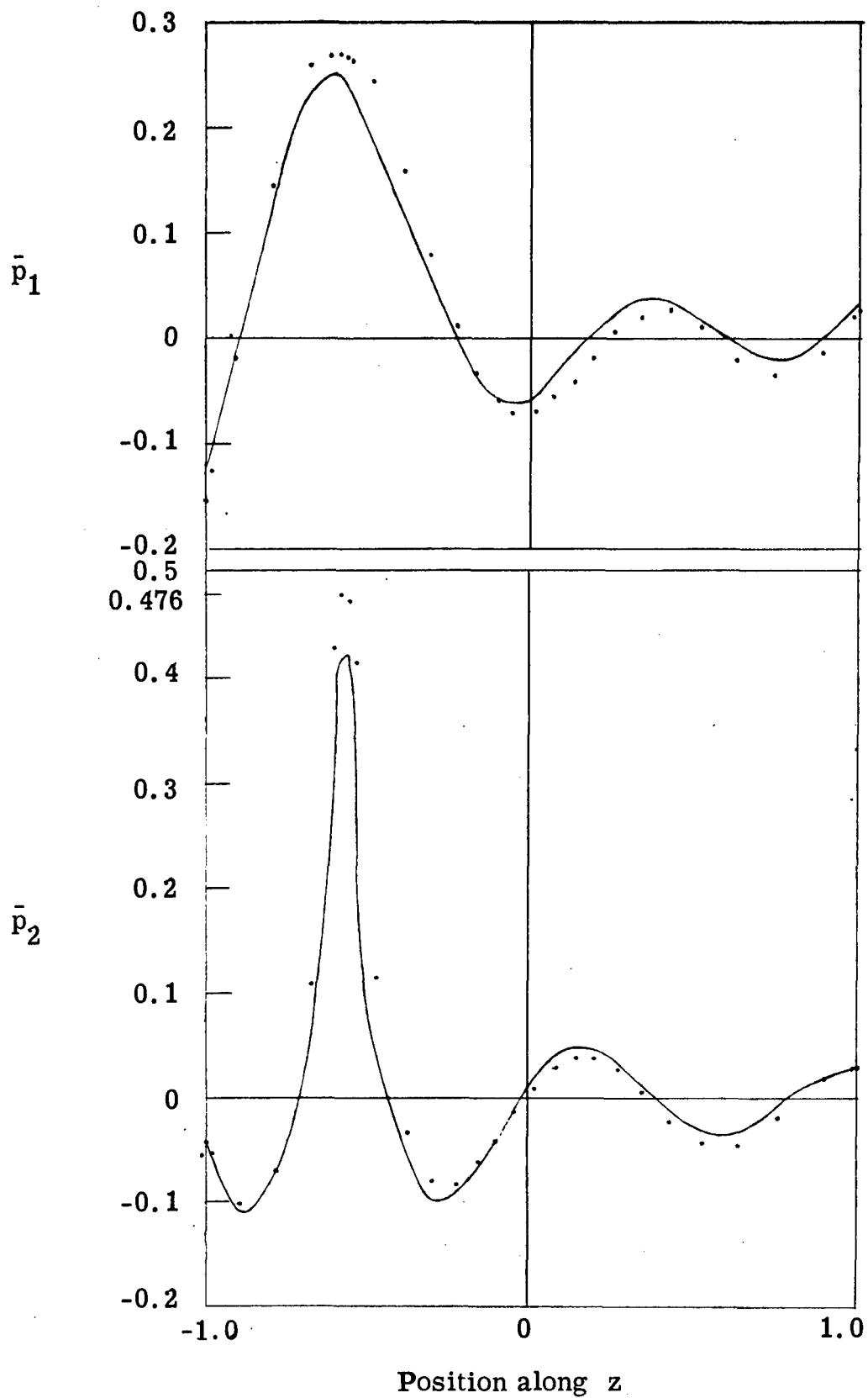
Model G, $ka = 7.26$



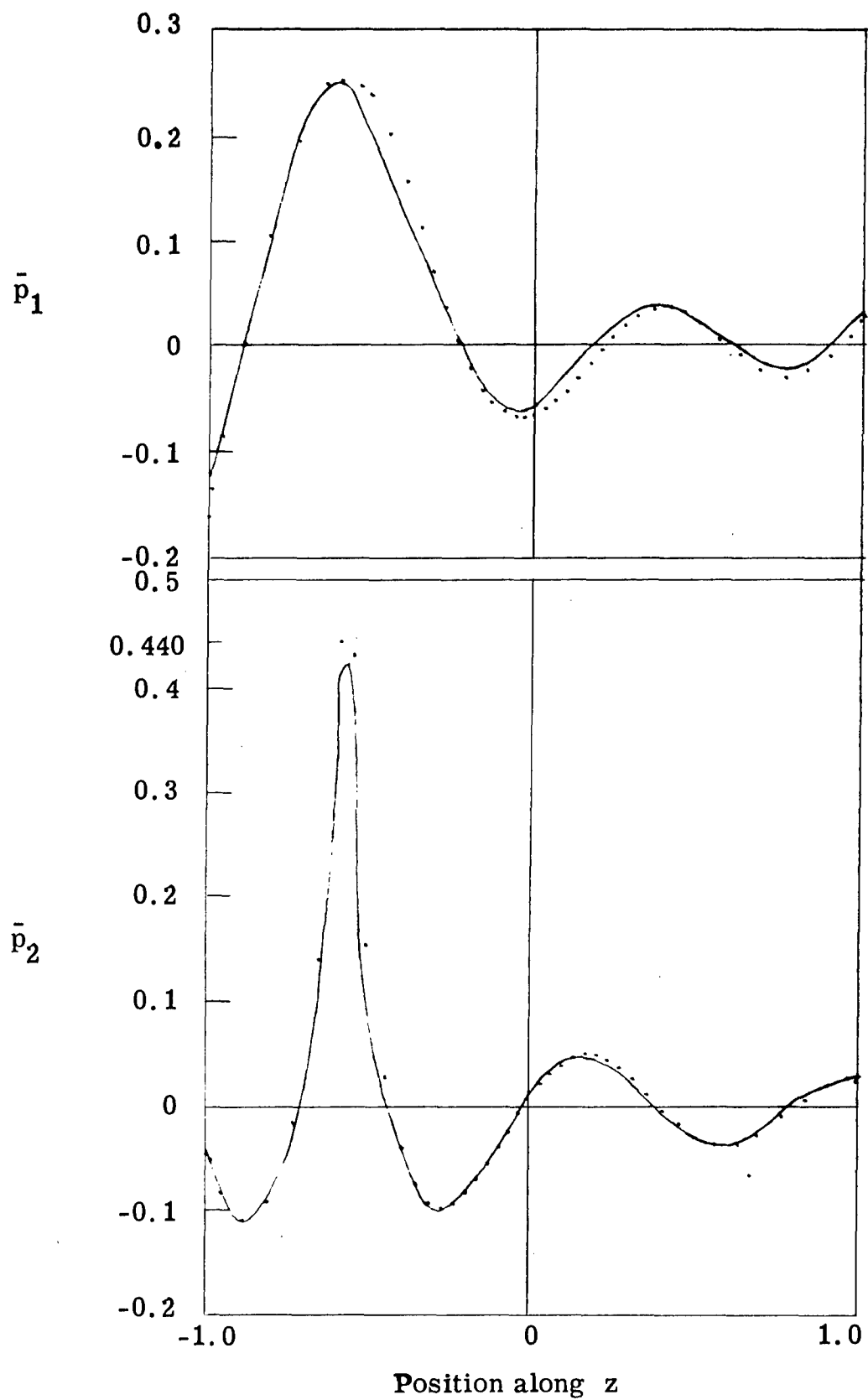
Model H, $ka = 7.26$



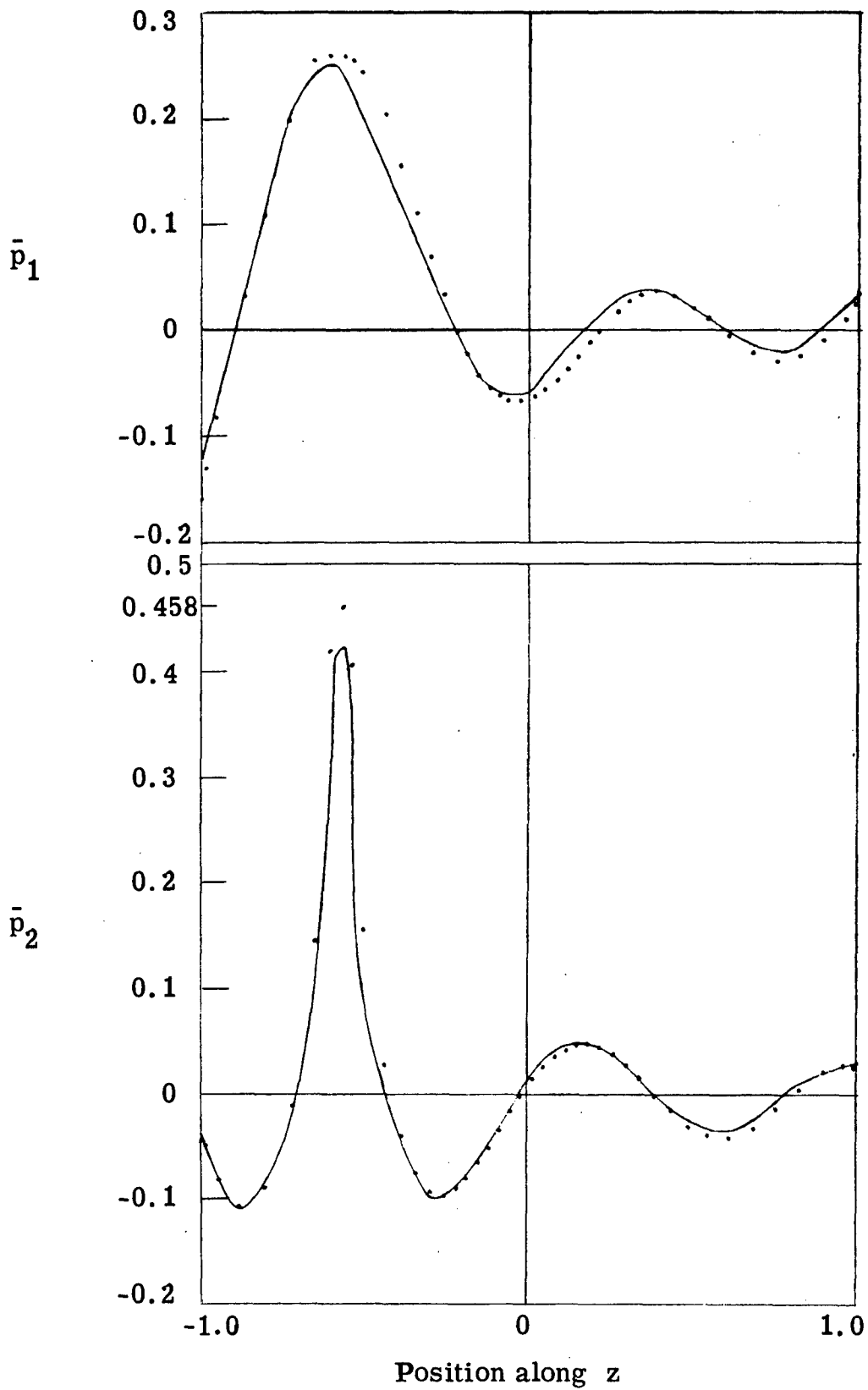
Model L, $ka = 7.26$



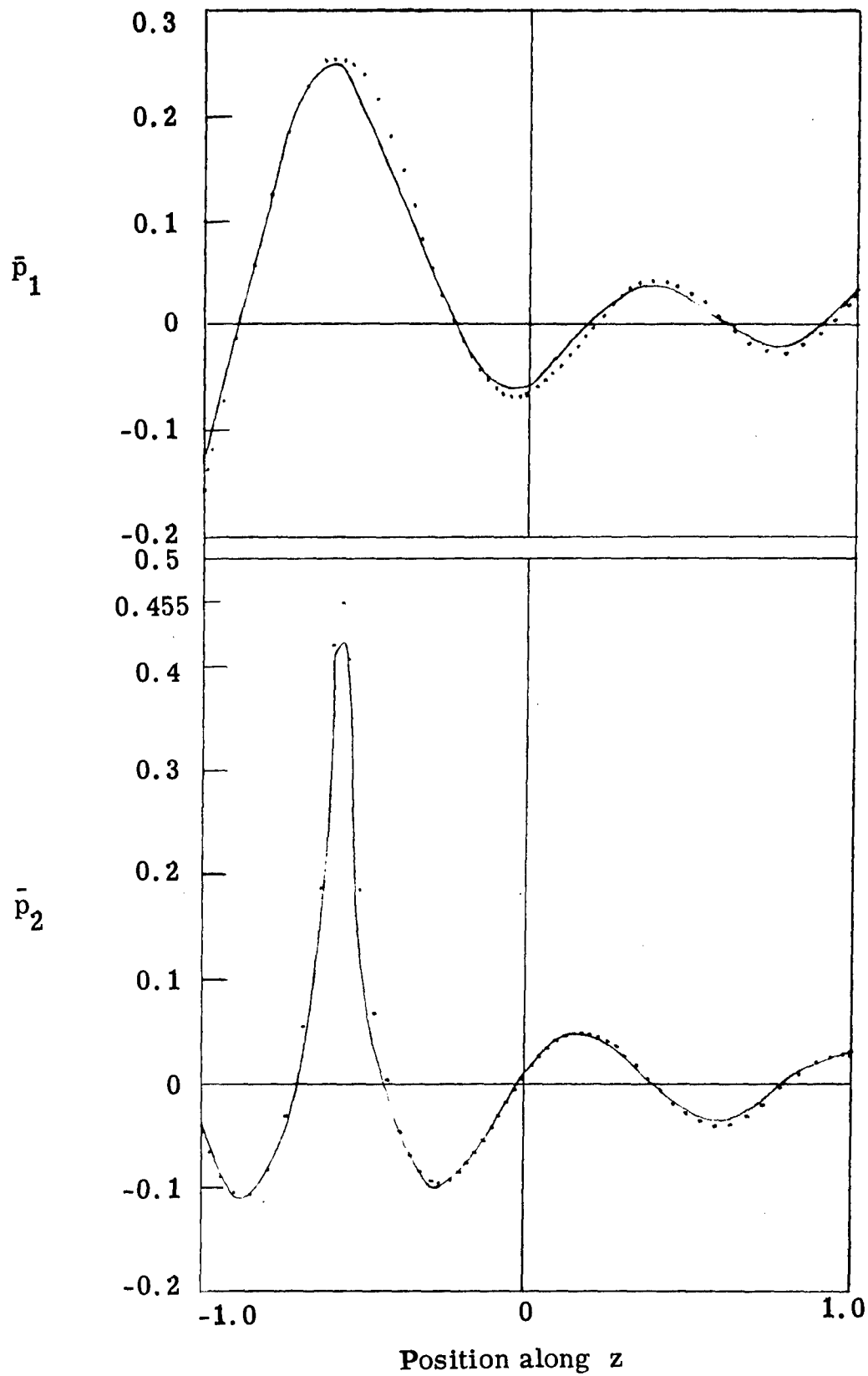
Model M, $ka = 7.26$



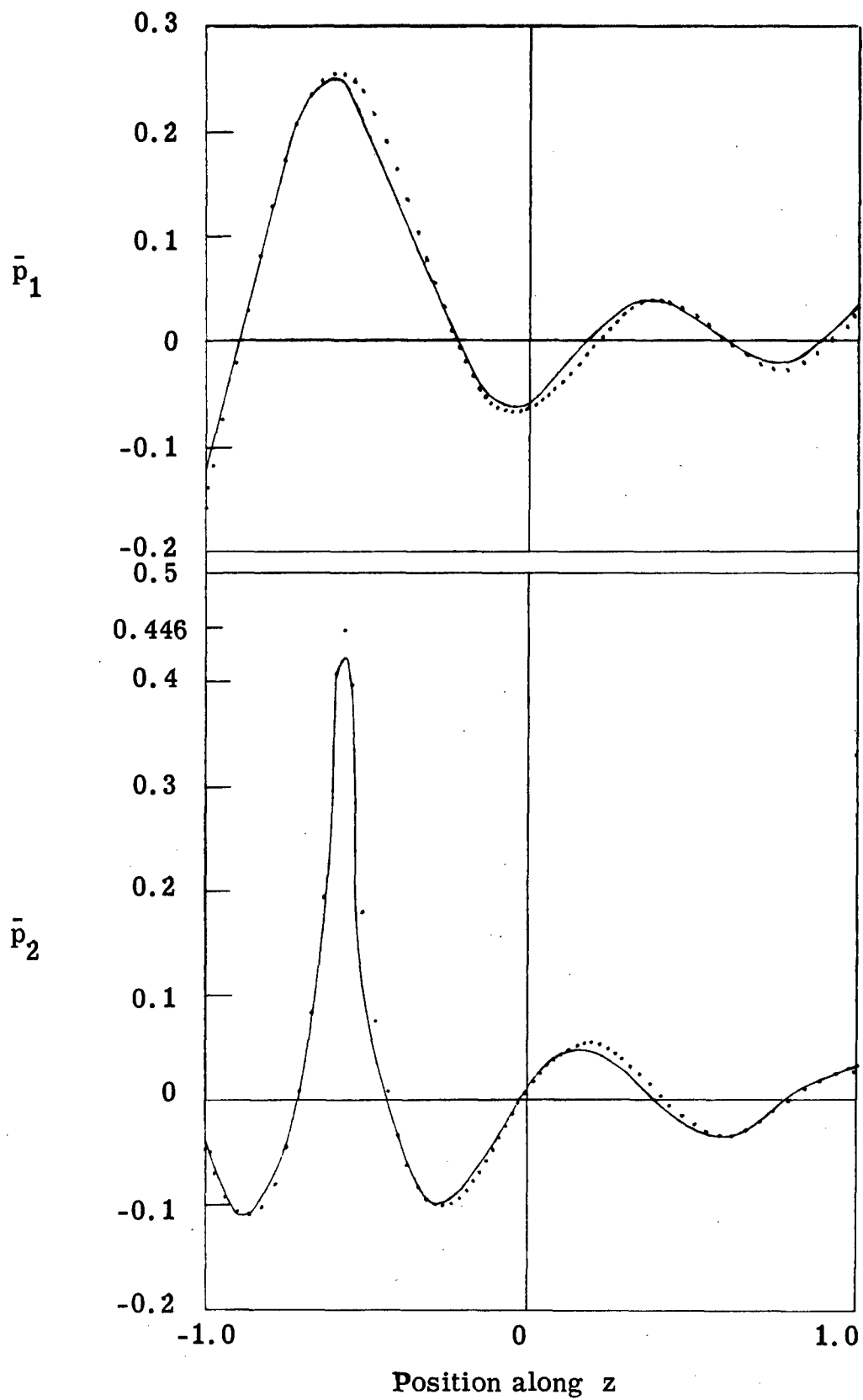
Model D, $ka = 7.26$



Model I, $ka = 7.26$



Model J, $ka = 7.26$



Model K, $ka = 7.26$

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13. ABSTRACT <p>This report investigates a technique for numerically calculating the sound pressure on a submerged spheroidal baffle that has a narrow ring piston vibrating at a near-critical frequency.</p> <p>The Helmholtz integral equation relating surface pressure and velocity normal to the structural surface is used to formulate the radiation problem. In the numerical calculation, this equation is represented by approximating matrix equations. These matrix equations correspond to a representation of the shell surface by a finite network of surface elements.</p> <p>The conditioning of the matrix equation near a critical frequency may make it necessary to use special techniques of solution to obtain the unique surface pressure. One method of dealing with this problem is described here.</p> <p>Solving the matrix equations by direct methods, we note that the pressure solution near the critical frequency is very sensitive to the way in which acoustic elements are distributed on the surface. Specifically, element distributions biased toward the active zone tend to cause the solution to diverge, primarily in the neighborhood of the zone, whereas distributions favoring the inactive region tend to cause the solution to converge.</p> <p>These observations provided a basis for the empirical approach to surface model refinements used for this investigation.</p> <p>Calculated surface pressure curves obtained using the empirical approach show a trend toward agreement with a comparison curve selected from the literature.</p>			

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